Error Adaptive Transport Protocol in Variable Error Rate Environment for Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Networks (WSNs) are characterized by low capacity on each nodes and links. Wireless links have high bit error rate (BER) parameter that changes frequently due tothe changes on network topology, interference, etc. To guarantee reliability in an error-prone environment, a retransmission mechanism can be used. In this mechanism, the number of retransmissions is used as a parameter that controls reliability requirement level. In this paper, we propose an Error Adaptive Transport Protocol (EATP) for WSNs that updates the number of retransmissions regularly to guarantee reliability during bit error rate changes as well as to utilize energy effectively. The said algorithm uses local information, thus, it does not create overhead problem.

Key Words : Bit Error Rate, Error Adaptive Transport Protocol, Wireless Sensor Networks

Ⅰ. Introduction

In WSN, the network topology and condition change frequently that leads to variable error rate. To cope with regular error rate changes, a transport protocol which is adaptive with error changes is required. In this paper, we propose a mathematical model which estimates how many retransmissions are needed to reach reliability requirement. From the result, a protocol called "Error Adaptive Transport Protocol for Wireless Sensor Networks" is presented. The main idea of the protocol is for each node to estimate error rate based on acknowledgment messages and to adjust its number of retransmissions to satisfy reliability requirement and at the same time to consume least energy. In this protocol, each node uses acknowledgment information like other transport protocols and no overhead is required.

The remainder of the paper is organized as follows. In section II, we present a review of related works in transport protocol for WSNs. Our previous work [15] is discussed in more detail here because it is the basis of this paper. Section III shows our mathematical model that can be used to estimate number of transmissions in each node. From the above result, an error adaptive transport protocol is proposed in section IV. Using ns-2 [16], we evaluate the protocol by two cost metrics which are probability of error of sending a packet which represents reliability level and number of hops of a packet which represents energy consumption in section V. Section VI draws the conclusion and summarizes the current result and future works.

Ⅱ. Related works

References [4-13] research on transport layer protocols. In these papers, they introduce the position and role of transport layer in WSNs. Two most important roles are reliability and congestion control. A good protocol does not only guarantee two such goals but should also be an energy-efficient protocol. Reliability and energy-efficient characteristics should be incorporated in the transport layer for WSNs.

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References [4] and [5] give an introduction to the reliable data transport problem and surveys protocols and approaches, often developed for particular applications to reflect the application specific dependability requirements. Moreover, they list some existing transport protocols for WSN. These protocols are classified, compared, and commented with some advantages and disadvantages. To explore reliability at the transport layer, RMST (Reliable Multi-Segment Transport) is presented in [6]. The protocol is designed to run above Directed Diffusion in order to support applications that require transfer of large data (JPEG, MPEG file). RMST guarantees reliable delivery of fragments from source to sink correctly. The protocol does not propose a retransmission number. The event-to-sink reliable transport (ESRT) protocol [7], a novel transport solution was developed to achieve reliable event detection in WSN with minimum energy expenditure. While RMST guarantees reliability of each fragment, ESRT guarantees reliability of whole data stream. ERST only suit applications that sink can receive collective information from many different sources. ERST does not use acknowledgment and retransmission mechanism.

Although some researches focused on transport protocols for WSNs are presented but the relationship between reliability and energy consumption has not been shown clearly. This is the reason why we conducted our research to estimate reliability level and energy consumption in [15]. The paper proposes a probability model that can be applied in transport protocols using hop-by-hop and end-to-end mechanisms. From this model, we evaluate the number of hops that a packet has to pass when it is being sent from source to destination and the probability of the event that a packet cannot reach its destination successfully after the number of transmissions reaches its maximum. This number of hops can represent energy consumption while error probability can represent the reliability level. The result from this model shows that reliability and energy consumption have contra-variant relationship, so we need a trade-off between reliability and energy-efficiency. The probability model will be reviewed in the mathematical model section of this paper.

This paper is an extension of the previous work. We propose a mechanism in which a node can estimate error condition in the network based on received acknowledgment message. Using the model in [15], we can solve optimal number of transmissions with respect to error condition. This optimal number guarantees that network can reach reliability requirement level and consumes least energy.

Ⅲ. Mathematical Model

3.1 Network model

Now, we consider hop-by-hop and end-to-end mechanisms in more detail (Fig. 1). For example, a packet needs to be transferred from node 1 (source) to node 8 (destination). To reach its destination, the packet passes through the path (1-->4-->5-->8) as indicated in the diagram using the heavy line. If every node in the path implemented error detection, receiver feedback, and retransmission, we call that the network uses hop-by-hop mechanism.

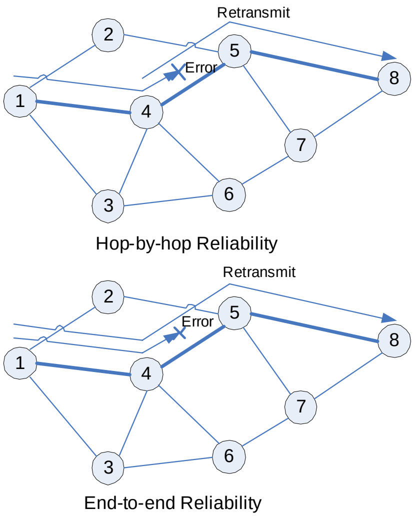

Fig. 1. Hop-by-hop and end-to-end mechanism

Otherwise, if only sources and destinations guarantee reliability, and other intermediate nodes just forward packets, we call that the network uses end-to-end mechanism. A key difference between hop-by-hop and end-to-end mechanism is when an error occurs, in hop-by-hop case, intermediate node retransmits the packet, but in end-to-end case, the packet needs to be sent from the source.

Let us review the probability model which can be used to estimate the number of hops of a packet from source to destination and the reliability of the network [15]. The parameters are summarized as follows:

- n: Number of hops between source and destination. In the previous example, if the path is 1-->4-->5-->8, then the number of hops is 3.
- P_h: Error rate. This is probability of error for a single attempt across one hop.
- R: Maximum number of transmissions, which is maximum number of times that a node transmits a packet.
- P_e: Probability of error, which is probability of event that a packet cannot reach its destination after using retransmission.
- ϵ: Maximum probability of error, which is a required threshold of P_e.

In the next parts of this section, we will show the algorithm to estimate network error condition and to update the control variable R to guarantee reliability, i.e., the probability of error P_e should be smaller than the error threshold ϵ.

3.2 Error rate estimation

Clearly, each node can receive an error rate information from the network links. But the operation of sending error condition information from links to nodes leads to overhead problem in networks. We can estimate error rate by using local and acknowledgment information to overcome the problem. In each duty cycle, each node can count the number of packets sent from it and the number of packets which have been acknowledged successfully to compute error rate as follows.

3.2.1 End-to-end mechanism

In end-to-end mechanism, only sources monitor network error rate. Each source computes probability of an event that a packet is in error in its way from the source to the destination is given by the following equation:

$$P_e = \frac{SN - AN}{SN} \tag{1}$$

where

- SN: Number of packets which are sent in each duty cycle
- AN: Number of packets which have acknowledgment from its destination.
- P_e: Probability of the event that packet cannot reach its destination.

Alternatively, the probability of sending a packet unsuccessfully after R transmissions from its source to its destination is [15]

$$P_e = 1 - \left(1 - P_h^R\right)^n \tag{2}$$

where

- R: Maximum number of transmissions.
- n: Distance from the source to the destination.
- P_h: Probability of error for a single attempt across one hop.

From Eqs. (1) and (2), we obtain:

$$P_h = 1 - \left(1 - \left(\frac{SN - AN}{SN}\right)^{1/R}\right)^{1/n} \tag{3}$$

SN and R are local information in each source. AN can be obtained by receiver feedback while n is from lower layer (network layer). Eq. (3) shows that each source can estimate network error rate cheaply because most of the information is local, and receiver feedback is not expensive.

3.2.2 Hop-by-hop mechanism

In hop-by-hop mechanism, not only the source but also every intermediate nodes monitor network error rate. While each source monitors error from itself to the destination in end-to-end mechanism, each node in hop-by-hop mechanism monitors error from itself to its next node in the path only. The probability of error for sending a packet from a node to its next node can be computed by as

$$P_R = \frac{SN - AN}{SN} \tag{4}$$

where P_R is probability of error for a R attempts across one hop.

At the same time, the probability of an event that a packet cannot reach destination after R transmissions is given by [15]

$$P_R = P_h^R \tag{5}$$

From Eqs. (4) and (5), we can obtain:

$$P_h = \left(\frac{SN - AN}{SN}\right)^{1/R} \tag{6}$$

Similarly, Eq. (6) shows that each node can estimate network error rate cheaply.

3.3 Updating maximum number of transmissions.

We adjust maximum number of transmissions R to guarantee reliability requirement with respect to error rate changes. The optimal value of the parameter yields guaranteed reliability from source to destination and consumes least energy to send the packet.

3.3.1 End-to-end mechanism

The maximum number of transmission R is satisfied [15]:

$$R > \frac{\log \varepsilon}{\log\left[1 - (1 - P_h)^n\right]} \tag{7}$$

Because energy consumption is an increasing function of R [15], so R is the smallest integer which satisfies (7), thus optimal number of transmissions R is given by

$$R_{opt.} = \left\lceil \frac{\log \varepsilon}{\log\left[1 - (1 - P_h)^n\right]} \right\rceil \tag{8}$$

Note that notation $\lceil x \rceil$ is the smallest integer which is greater than x.

3.3.2 Hop-by-hop mechanism

The maximum number of transmission R is also satisfied [15]:

$$R > \frac{\log\left[1 - (1 - \varepsilon)^{1/n}\right]}{\log P_h} \tag{9}$$

Similarly, R is the smallest integer which satisfies (9), thus the optimal number of transmissions R is given by

$$R_{opt.} = \left\lceil \frac{\log\left[1 - (1 - \varepsilon)^{1/n}\right]}{\log P_h} \right\rceil \tag{10}$$

Ⅳ. Error Adaptive Transport Protocol

4.1 End-to-end mechanism

In this mechanism, most protocol operations are implemented in sources. Destination sends acknowledgment messages back to source while intermediate nodes just forward messages whatever messages they received. Thus, we only present source operations here.

When an application needs to send data the source stores a copy of the packet in its buffer to retransmit if necessary. At the same time, a retransmission timer is raised (Fig. 2(a)).

If the source receives acknowledgment message, it will release the copy of the corresponding packet and consider that the packet reaches its destination successfully (Figs. 2(b), 3(a)).

If the retransmission timer expires and the packet has not been acknowledged yet, the source will retransmit the packet (Figs. 2(c), 3(b)). If number of transmissions reaches its maximum, the

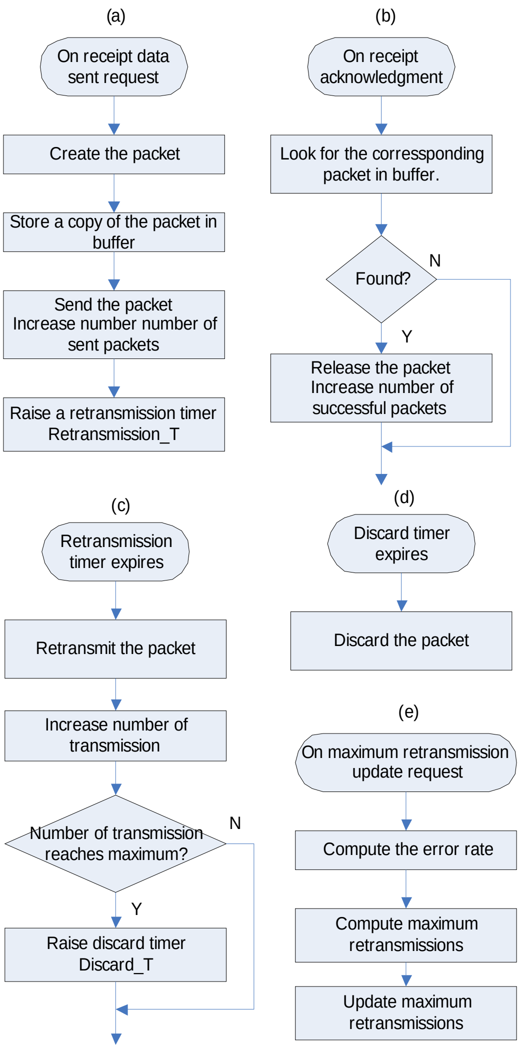

Fig. 2. End-to-end source operations include (a) sending packet, (b) receiving acknowledgment, (c) retransmitting, (d) discarding, and (e) updating number of transmissions.

packet is marked for discarding. If the discard timer expires and the packet has not been acknowledged yet then the packet is discarded, and is considered to be error (Figs. 2(d), 3(c)).

Finally, the source counts the number of sent packets and the number of successful packets (i.e. packets have been acknowledged) in every duty cycle. It computes error rate using (3) and optimal number of transmission using (8). At the end of duty cycle, the transmission number is updated with new optimal value (Fig. 2(e)).

4.2 Hop-by-hop mechanism

Different from end-to-end mechanism, all source and intermediate nodes monitor and update number of transmissions. But the hop-by-hop source operations are almost the same as the end-to-end source operations. The differences are that hop-by-hop sources compute error rate using (6) instead of (3) and optimal number of transmissions using (10) instead of (8). Intermediate nodes do not only forward but also guarantee reliability. Similar to the source, a copy of the packet is stored in the buffer before forwarding to retransmit if necessary. Intermediate nodes also count the number of sent packets and number of successful packets to estimate error rate and to update maximum number of transmissions.

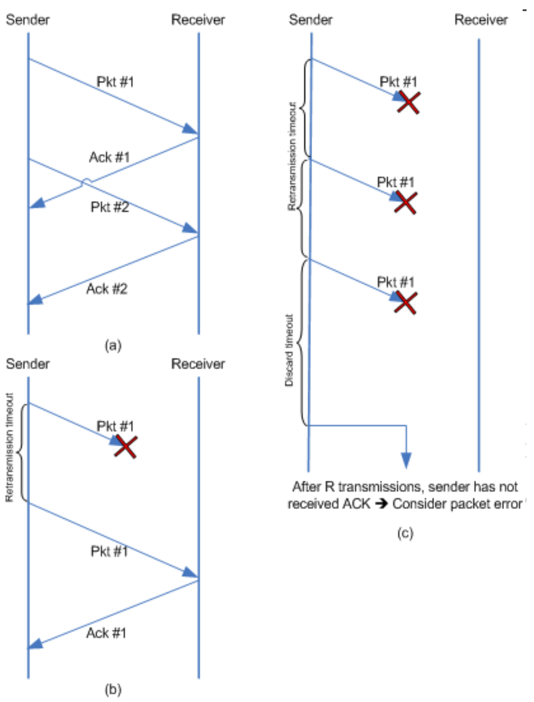

Fig. 3. Node operations: (a) Sending and receiving in normal case, (b) Retransmission if message is in error, (c) Stopping retransmission if number of transmission reaches its maximum, the message is considered in error.

Intermediate nodes have the following operations: receiving a packet, retransmitting, discarding, and updating the number of transmissions. The three latter operations are the same as the ones of source operations. The receiving operation is shown in Fig. 4.

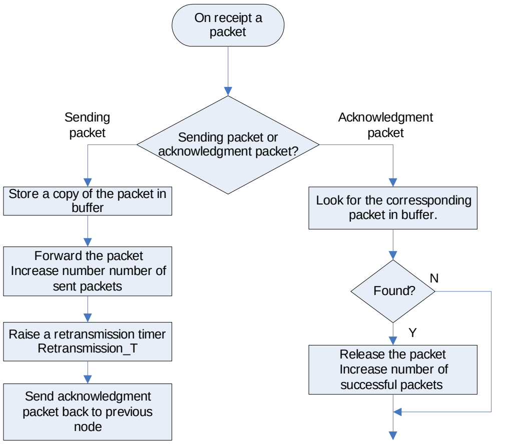

Fig. 4. Receipt a packet of an intermediate node Hop-by-hop mechanism.

If the packet is sending one, the node needs to forward the packet to the next node. Similar to the source, a copy of the packet is stored in the buffer to retransmit, if necessary. The node also sends acknowledgment packet back to the previous node. The corresponding packet is released if the packet is an acknowledgment one.

V. Simulation

To evaluate the protocol for WSN, we will simulate WSN model (using ns-2 [16]). In this simulation, we consider the network which has the following model (Fig. 5). Assume that an application in node 1 needs to send data to node 8 with reliability requirement which can be represented that probability of error should be smaller than 5%. Here, we do not focus on routing problem, so we assume that routing path is fixed and it is 1-->4-->5-->8. Since the network size is small and nodes are homogeneous, we assume that error rates are the same at every link. Let the error rate vary randomly from 0.01 to 0.3. The following table shows the probability of error and average number of hops that each message has to pass to reach its destination with respect to maximum number of transmissions. The two last rows show the result of our proposed protocol, the previous one is the result from end-to-end mechanism and the last one is the result from hop-by-hop mechanism.

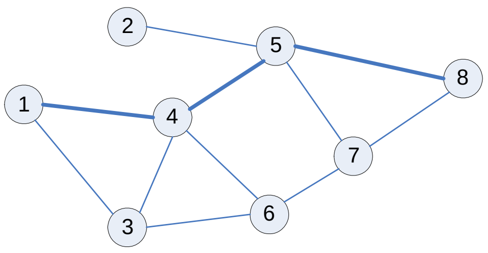

Fig. 5. Network topology

Observe that when the maximum number of transmissions increases, the probability of error decreases. This means that reliability increases and at the same time the average number of hops increases, i.e., network consumes more energy [15].

Table 1. Error probability and estimated number of hops

Transmission number	Error probability	Estimated number of hops
1	0.3340	2.6183
2	0.1460	3.4419
3	0.0760	3.8060
4	0.0405	3.9976
5	0.0242	4.0865
6	0.0138	4.1387
7	0.0080	4.1712
8	0.0051	4.1943
9	0.0031	4.1932
10	0.0021	4.2097
Adaptive end-to-end number	0.0329	4.0245
Adaptive hop-by-hop number	0.0433	3.51130

To evaluate the performance of our protocol, we compare two cases, one uses our protocol to update maximum number of retransmissions frequently according to error rate changes and one uses a fix maximum number of transmission. Our algorithm have probability of error smaller than error threshold $\epsilon = 0.05$ (reliability requirement). The average numbers of hops are 4.0245 and

3.5130 (Table 1). If we use fix maximum number of transmissions and this number is smaller than or equal to 3, the probability of error is greater than 0.05 (Fig. 6) that means the network cannot reach the reliability requirement. If the maximum number of retransmission is greater than 3, the reliability requirement can be reached but average number of hops is high in comparison with our average number of hops. Thus adaptive error protocol can guarantee reliability requirement and at the same time it consumes least energy.

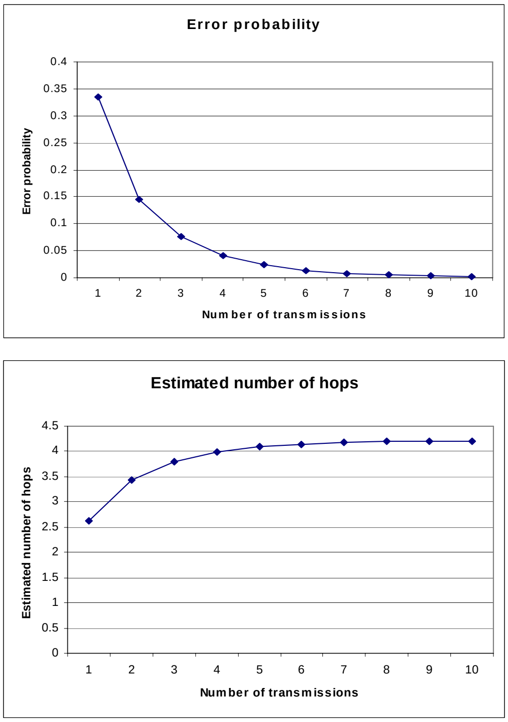

Fig. 6. Error probability and estimated number of hops

In addition, the protocol can guarantee reliability in a stable way. In Fig. 7, the probability of error in EATP variesround error threshold ϵ=0.05, i.e. the network is reliable most of time. If R is 1, the probability is much greater than error threshold ϵ=0.05, that means the reliability is not met. In the case of R=10, reliability is met but the network consumes much energy. Moreover when the number of transmission is 3; the network is only reliable if error rate is small and not reliable if error rate is high. For example, when error rate is smaller than 0.05, error probability is acceptable, but when error rate is larger than 0.1, error probability exceeds the error threshold ϵ=0.05 (Fig. 7). It is because when error rate varies, in EATP, the maximum number of hops changes to satisfy the new error rate. There are exceptions, i.e., the probability of error in EATP exceeds the error threshold; it is because the protocol has delay for updating maximum number of transmissions. But if we use fixed maximum number of transmissions and if error rate is small, we can exceed reliability requirement and hence waste energy. Furthermore, if the error rate is high, reliability requirement is not met. Our protocol problem is that each node needs more capacity and consumes energy to maintain its buffer.

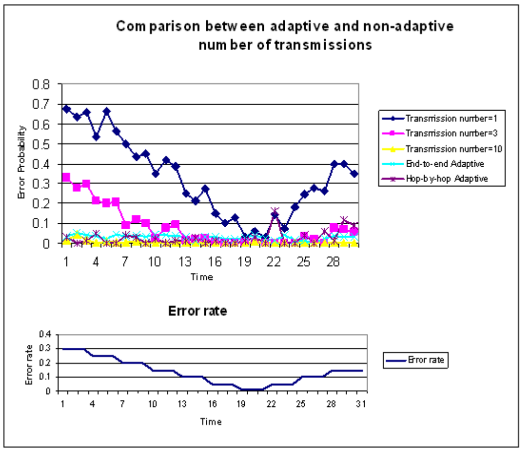

Fig. 7. Comparison between adaptive and non-adaptive number of transmissions

Furthermore, we can compare between hop-by-hop and end-to-end mechanism. In this paper, we consider an adaptive mechanism in time domain, i.e., the protocol updates its control variable frequently with respect to the error rate. But the error rate is not only variable in time domain but also in spatial domain this means that it varies from link to link. Thus hop-by-hop can be considered an adaptive mechanism in spatial domain, i.e., in an environment where error rates vary from link to link, we should use hop-by-hop mechanism.

Ⅵ. Conclusion

Transport protocols play an important role in supporting reliability in Wireless Sensor Networks. In this paper, we propose a probability model which can be used to estimate error rate and to update maximum number of transmission corresponding to error rate changes. From the result, we present an error adaptive transport protocol which can be applied in an environment where network error changes frequently. The protocol can run in two modes: hop-by-hop and end-to-end. In end-to-end mode, only sources and destinations compute and update the number of transmissions, while intermediate nodes only forward the packet. On the other hand, every node maintains the number of transmissions in hop-by-hop mode. If environment error rate is variable in the time domain, the protocol works well in end-to-end mode. If environment error rate is variable in both time and spatial domains, the protocol should operate in hop-by-hop mode. The simulation result shows that EATP is not only reliable and stable but also energy-efficient.

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